On the Origin of the Highest Energy Cosmic Rays

F. W. Stecker
Laboratory for High Energy Astrophysics, Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

We present the results of a new estimation of the photodisintegration and propagation of ultrahigh energy cosmic-ray (UHCR) nuclei in intergalactic space. The critical interactions for energy loss and photodisintegration of UHCR nuclei occur with photons of the infrared background radiation (IBR). We have reexamined this problem making use of a new determination of the IBR based on empirical data, primarily from IRAS galaxies, and also collateral information from TeV γ-ray observations of two nearby BL Lac objects. Our results indicate that a 200 EeV Fe nucleus can propagate ~ 100 Mpc though the IBR. We argue that it is possible that the highest energy cosmic rays observed may be heavy nuclei.

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Shortly after the discovery of the cosmic microwave background radiation (CBR), it was shown that cosmic rays above $\sim$100 EeV (10^{20}eV) should be attenuated by photomeson interactions with CBR photons [1]. It was later calculated that heavier nuclei with similar *total* energies would also be attenuated, but by a different process, *viz.*, photodisintegration interactions with IBR photons [2]. The particular detections of two events with energies well above these expected cutoffs, one at ~ 200 EeV [3] and one at ~ 300 EeV [4] have provided a double problem for cosmic-ray physicists. How does nature accelerate particles to these extreme energies and how do they get here from extragalactic sources [5]? To answer these questions, new physics has been invoked, physics involving the formation and annihilation of topological defects (TDs) which may have been produced in the very earliest stages of the big bang, perhaps as a result of grand unified theories. TD annihilation has unique observational consequences, such as the copious production of UHCR neutrinos and γ-rays [6] and an interesting satellite experiment called *OWL* has been proposed to test look for such consequences [7]. However, we will reexamine here the more conventional scenario by which UHCRs are accelerated at extragalactic sites.

Although cosmic acceleration to energies above 100 EeV pushes our present theoretical ideas to their extreme, it has been suggested that such acceleration may occur in hot spots in the lobes of radio galaxies [8]. For the purposes of this *Letter*, we will assume that such acceleration processes can occur in nature. We now turn specifically to the propagation problem. A UHCR proton of energy ~ 200 EeV has a lifetime against photomeson losses of $\sim 3\times10^{15}$s; one of energy 300 EeV has a lifetime of about half that [9]. These values correspond to linear propagation distances of ~ 30 and 15 Mpc respectively. Even shorter lifetimes were calculated for Fe nuclei, based on photodisintegration off the IBR [2]. Recent estimates of the lifetimes of UHCR γ-rays against electron-positron pair production interactions with background radio photons give values below 10^{15}s [10]. Within such distances, it is difficult to find candidate sources for UHCRs of such energies.

In this *Letter*, we present the results of a new estimation of the photodisintegration and propagation of UHCR nuclei through the IBR in intergalactic space. We have reexamined this problem making use of a new determination of the IBR based on empirical data, primarily from IRAS galaxies, recently calculated by Malkan and Stecker [11]. Malkan and Stecker calculated the intensity and spectral energy distribution (SED) of the IBR based on empirical data, some of which was obtained for almost 3000 IRAS galaxies. It is these sources which produce the IBR. The data used for this calculation included (1) the luminosity dependent SEDs of these galaxies, (2) the 60 μm luminosity function for these galaxies, and (3) the redshift distribution of these galaxies. The magnitude of the IBR flux derived by these authors is approximately an order of magnitude lower that that used by Puget, Stecker and Bredekamp [2] in their extensive examination of photodisintegration of UHCR nuclei. This determination of a lower value for the magnitude of the IBR is also indicated by the observed lack of strong absorption in the multi-TeV γ-ray spectra of the active galaxies known as the BL Lac objects Mrk 421 [12] and Mrk 501 [13]. The lack of an obvious absorption feature up to an energy greater than $\sim$ 5-10 TeV is consistent with the new, lower value for the IBR [14].

The Malkan-Stecker SED of the IBR has a similar shape to the one labeled “HIR” in the paper of Puget, *et al.* [2] in the mid-IR and far-IR range. However, it is approximately an order of magnitude lower in intensity. Therefore, one may replace the lifetimes given in ref. [2] by lifetimes which are longer by a factor of 10-20. Here we conservatively assume a factor of 10. Figure

1 is adapted from Fig. 14 of Puget, *et al* [2]. It indicates how a flux of UHCR Fe nuclei with an initial E^{-3} differential power-law spectrum will develop a cutoff at a critical energy, E_c which has an inverse dependence on the propagation time. In fact, for energies in the range near 200 EeV, $E_c \simeq 150(ct/100Mpc)^{-1/2}$ EeV.

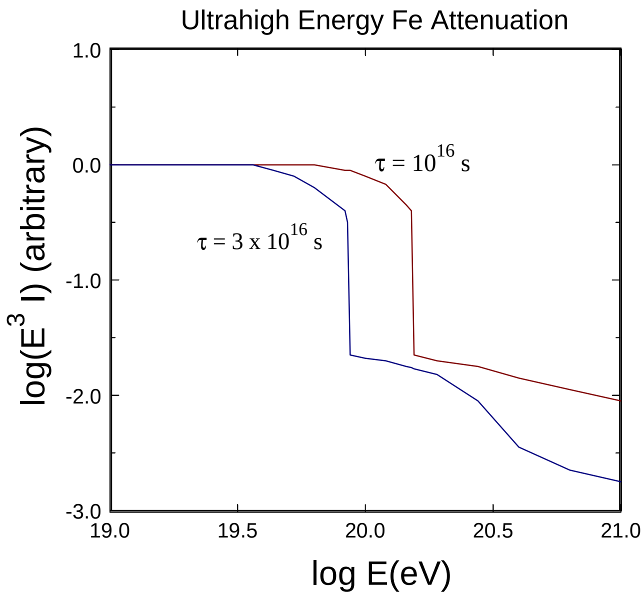

FIG. 1. Attenuated E^{-3} differential spectrum for ultrahigh energy Fe nuclei for propagation times as indicated.

We conclude from this that the highest energy CR induced air-showers could have been produced by UHCR nuclei propagating from a distance of the order of 100 Mpc! Stanev, Biermann and Lloyd-Evans [15] have examined the arrival directions of the highest energy air-shower events. These authors have pointed out that the 200 EeV event [3] is within 10° of the direction of the powerful radio galaxy NGC315 and the 300 EeV event is within 12° of the powerful radio galaxy 3C134. NGC315 lies at a distance of only ~ 60 Mpc from us. The distance to 3C134 is unfortunately unknown because its location behind a dense molecular cloud in our Galaxy obscures the spectral lines required for a measurement of its redshift.

It should be also pointed out that it is reasonable to expect that the highest energy cosmic rays may be nuclei. This is because the maximum energy to which a particle can be accelerated in a source of a given size and magnetic field strength is proportional to its charge, Ze. That charge is 26 times larger for Fe than it is for protons. We conclude that is indeed possible that the highest energy cosmic rays which have been observed are heavy nuclei from radio galaxies which lie at distances within 100 Mpc from Earth.

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